Event Structure and Double Helicity Asymmetry in Jet Production from Polarized p+p Collisions at $\sqrt{s}$ = 200 GeV at PHENIX

SPIN 2010
Spin in Hadronic Reactions 1
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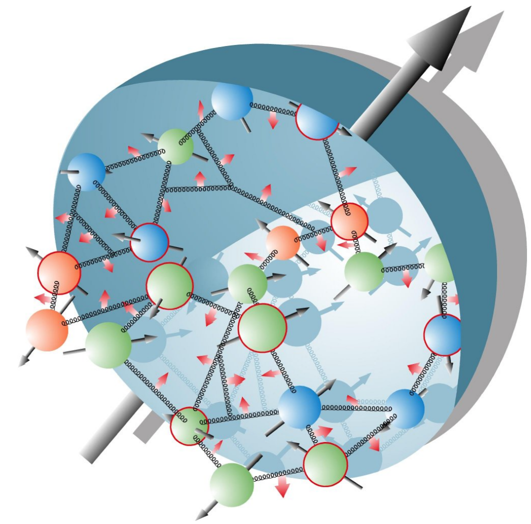
Contents

Introduction

- Spin structure of proton

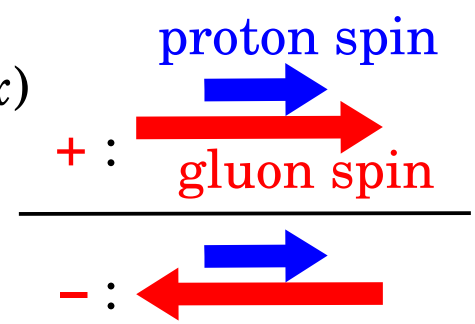
$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta G + L_q + L_g$$

proton spin | quark spin | gluon spin | orbital angular momenta



- Proton spin problem (1988 EMC experiment)
- By many DIS data, $\Sigma\Delta q = 0.330(39)$ at $Q^2 = 5$ GeV^2 [PRD75, 012007]
- Need determine the gluon polarization ΔG first by experiment

- Polarized (spin-dependent) gluon distribution function: $\Delta G(x)$

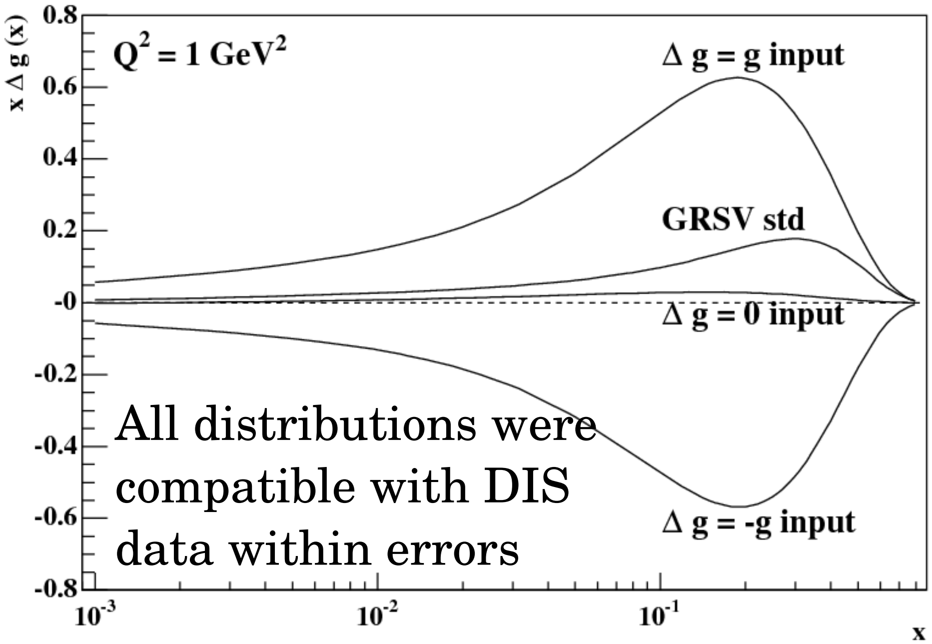


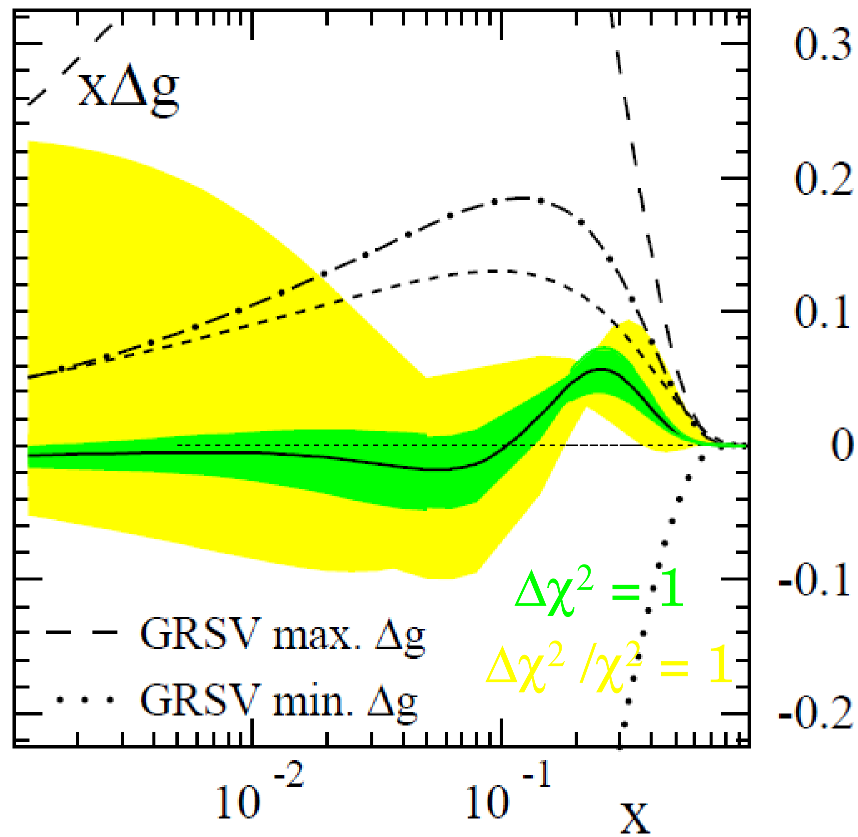
$$\Delta G = \int_0^1 dx \Delta G(x) = \int_0^1 dx (G^{+}(x) - G^{-}(x))$$

- Bjorken x: momentum fraction carried by a parton ($= p_{\mathrm{parton}}/P_{\mathrm{proton}}$)
- $G^{+}(x)$: the probability of finding gluons at x and "+" spin direction
- ΔG = the contribution of gluon spin to the proton spin

Introduction

- Knowledge on $\Delta G(x)$
  - GRSV ... PRD 63, 094005 (2001)
    - Many DIS data together were analyzed
    - Best-fit result and three typical distributions
  - DSSV ... PRL 101, 072001 (2008)
    - DIS, SIDIS & p+p data
    - Best-fit result w/ uncertainty bands

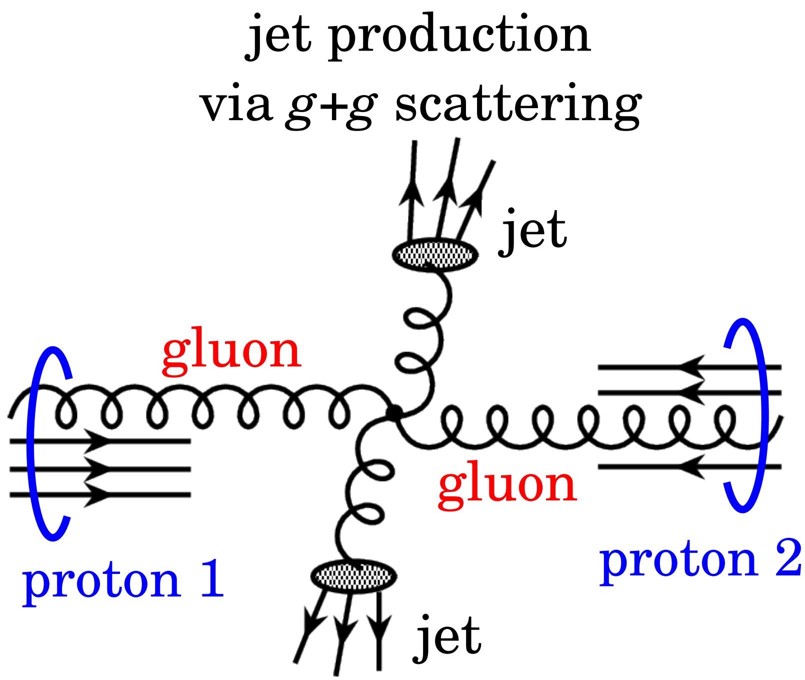




- Many data in ~8 years have improved the accuracy
- But still larger uncertainty, unclear x dependence

Introduction

- Polarized $p+p$ collisions for ΔG measurement
  - Jet, π^0, direct photon productions etc.
    via parton+parton scattering
  - Gluon can be involved at leading order
    (compared with lepton-nucleon DIS)
  - Suited for ΔG measurement

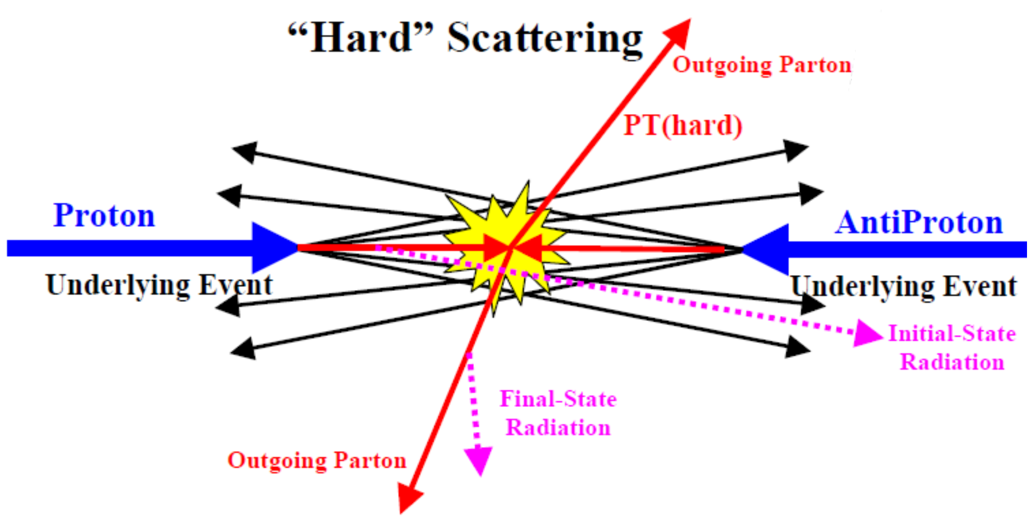


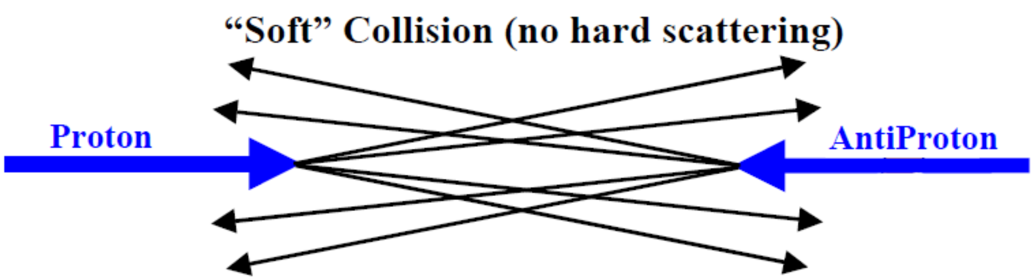
- Jet production in pol. $p+p$ collisions
  - Jet = a group of particles fragmented from a scattered parton
  - Dominating process in hard scatterings
    –> large statistics & few background events
  - $g+g$ & $g+q$ dominate (not $q+q$)
  - Better reconstruct the original parton kinematics and acquire better stat. accuracy at higher x (compared with inclusive hadron measurements)

- This is the first measurment of inclusive jet production at PHENIX to determine ΔG (arXiv:1009.4921)

Introduction

- Event structure of hadron-hadron collisions
  - Jet event = two jets + underlying event
    ≠ two jets + soft collision



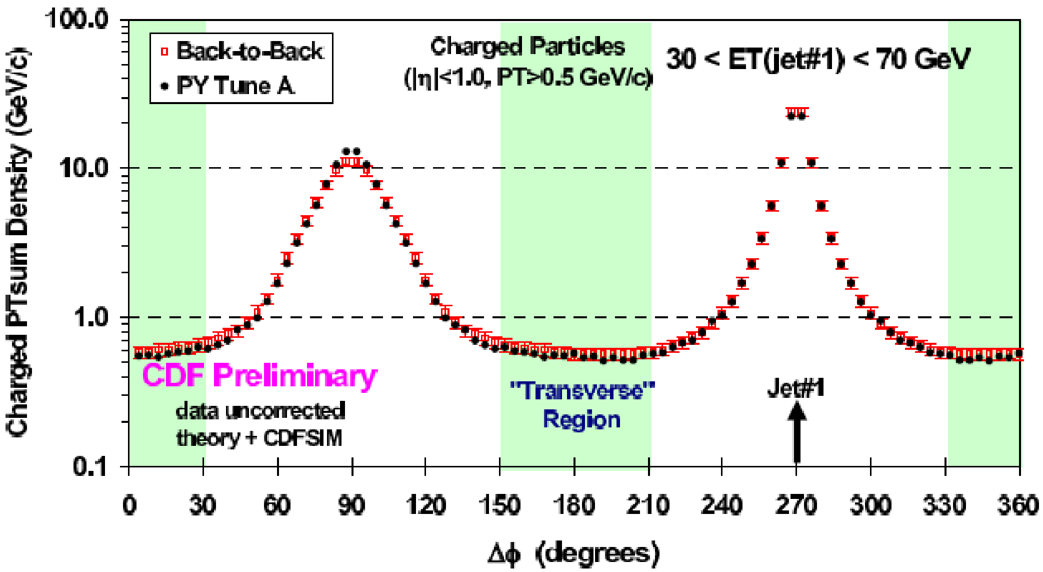


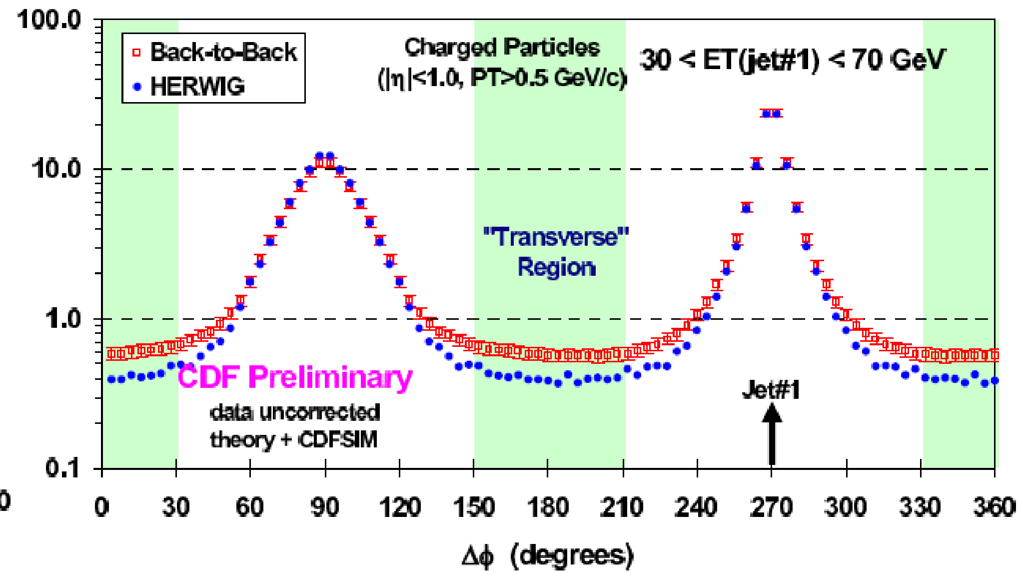
(pictures by CDF)

- Underlying event = particles not originating from hard scattering

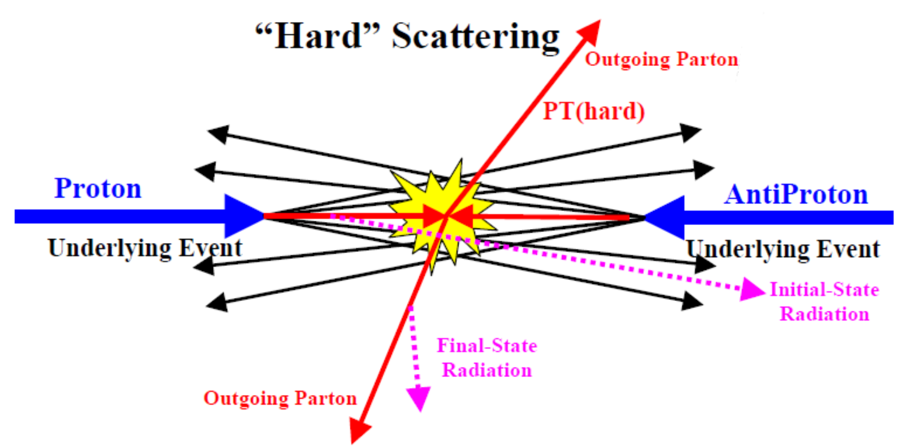
Introduction

- Event structure in $\bar{p}+p$ coll. at $\sqrt{s} \sim 2$ TeV measured by CDF
  - Charged particle p_T density as an example
    (“transverse” region is sensitive to underlying event)





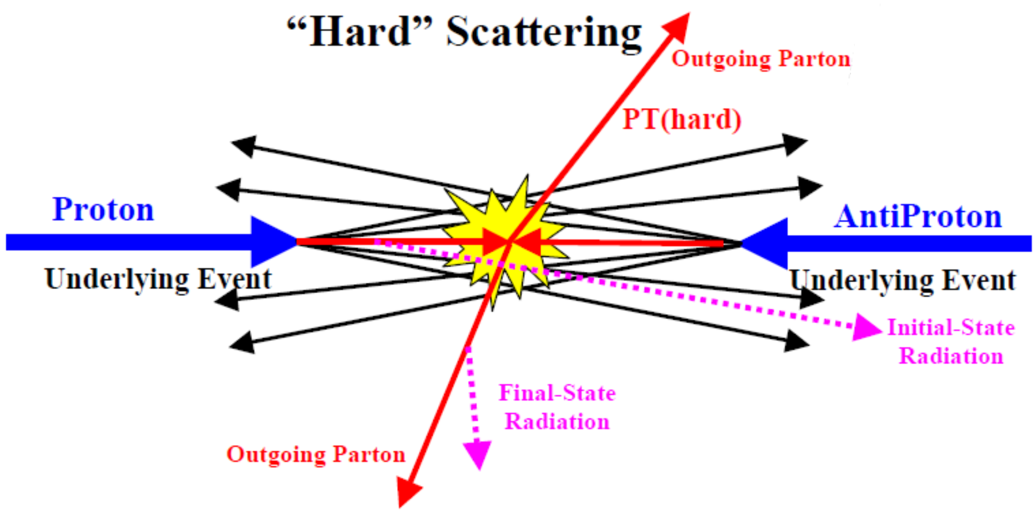
  - Two simulations (PYTHIA & HERWIG) well reproduce back-to-back jet shape
  - PYTHIA is better at “transverse” region



Introduction

- Multi-Parton Interaction (MPI) scheme in PYTHIA
  - Semi-hard parton+parton scatterings (as well as soft beam remnants)
  - Agreed well with CDF Run-2 data
  - Indicates an advanced scattering picture

    Jet event = two hard-scatterd partons + semi-hard-scat. partons + soft



- Measurement of event structure (underlying event) in *p*+*p* collisions at $\sqrt{s}$ = 200 GeV is intersting...
  - To evaluate correction for measured jet momentum (in ΔG measurement)
  - To examine MPI model

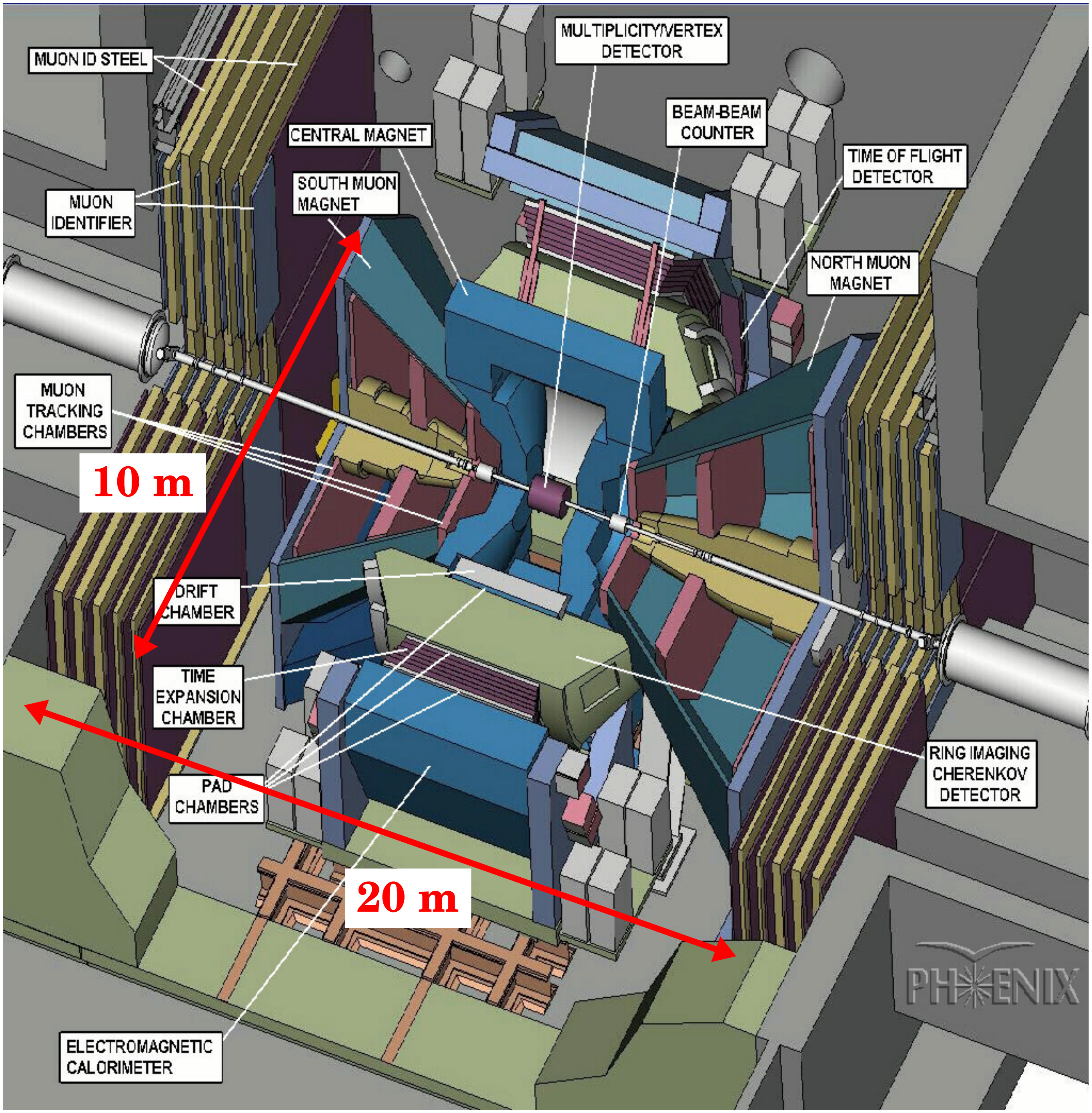
Experimental Setup

Relativistic Heavy Ion Collider (RHIC) @ BNL

- The unique collider for polarized proton-proton collision
- $\sqrt{s}$ = 200 GeV with 100 GeV proton + 100 GeV proton
  ($\sqrt{s}$ = 62.4 & 500 GeV are also possible)
- Longitudinal polarization (transverse pol. is also possible)

here

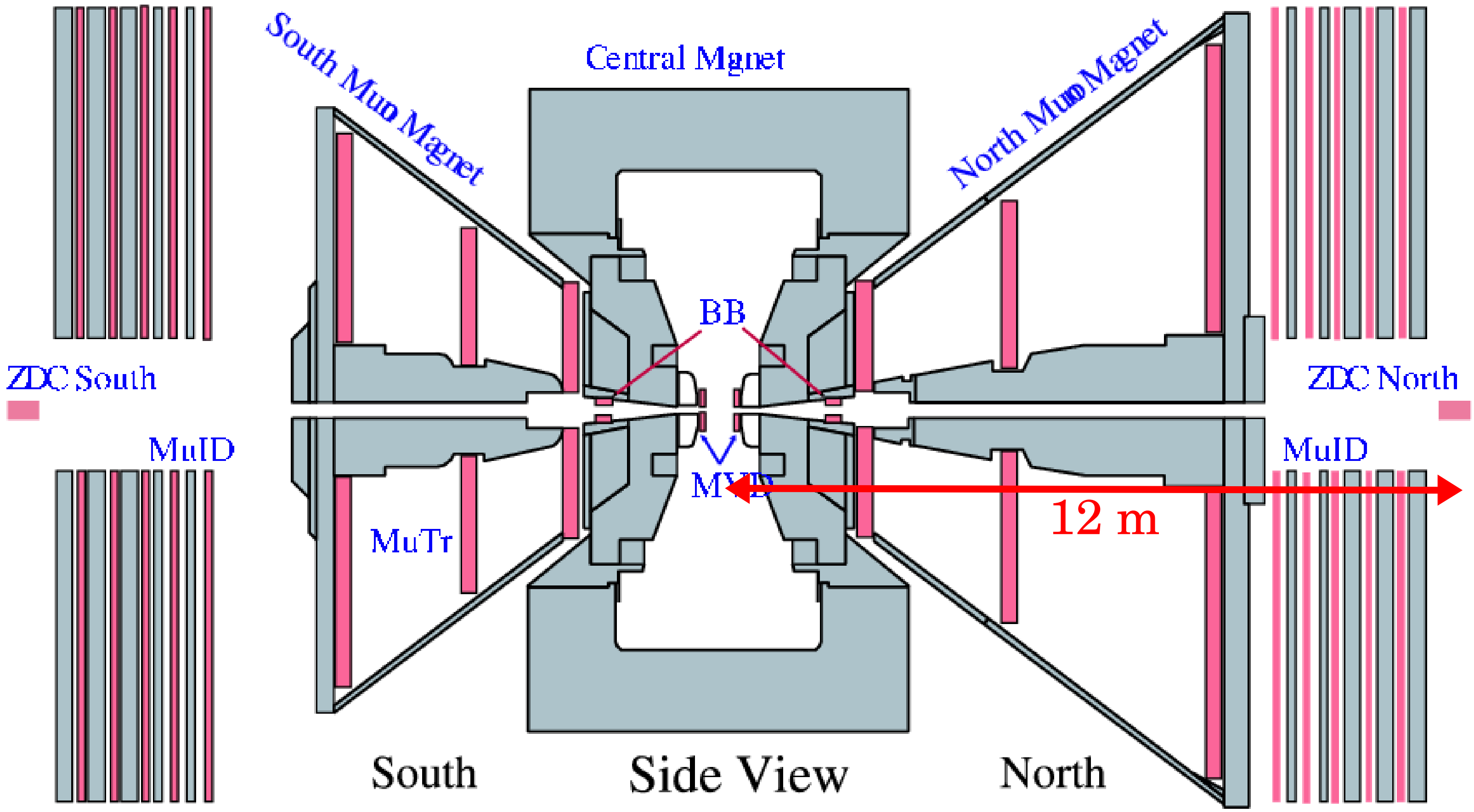
PHENIX Detector – Overview



- Forward detectors
  - Near beam pipe
- Central (East & West) Arms
  - pseudorapidity: $|\eta| < 0.35$
  - azimuthal: $\Delta\phi = 90^o \times 2$
- Muon (North & South) Arms
  - $1.1 < |\eta| < 2.3$,
  - $\Delta\phi = 2\pi$
  - muon

PHENIX Detector – Forward Detectors (near Beam Pipe)

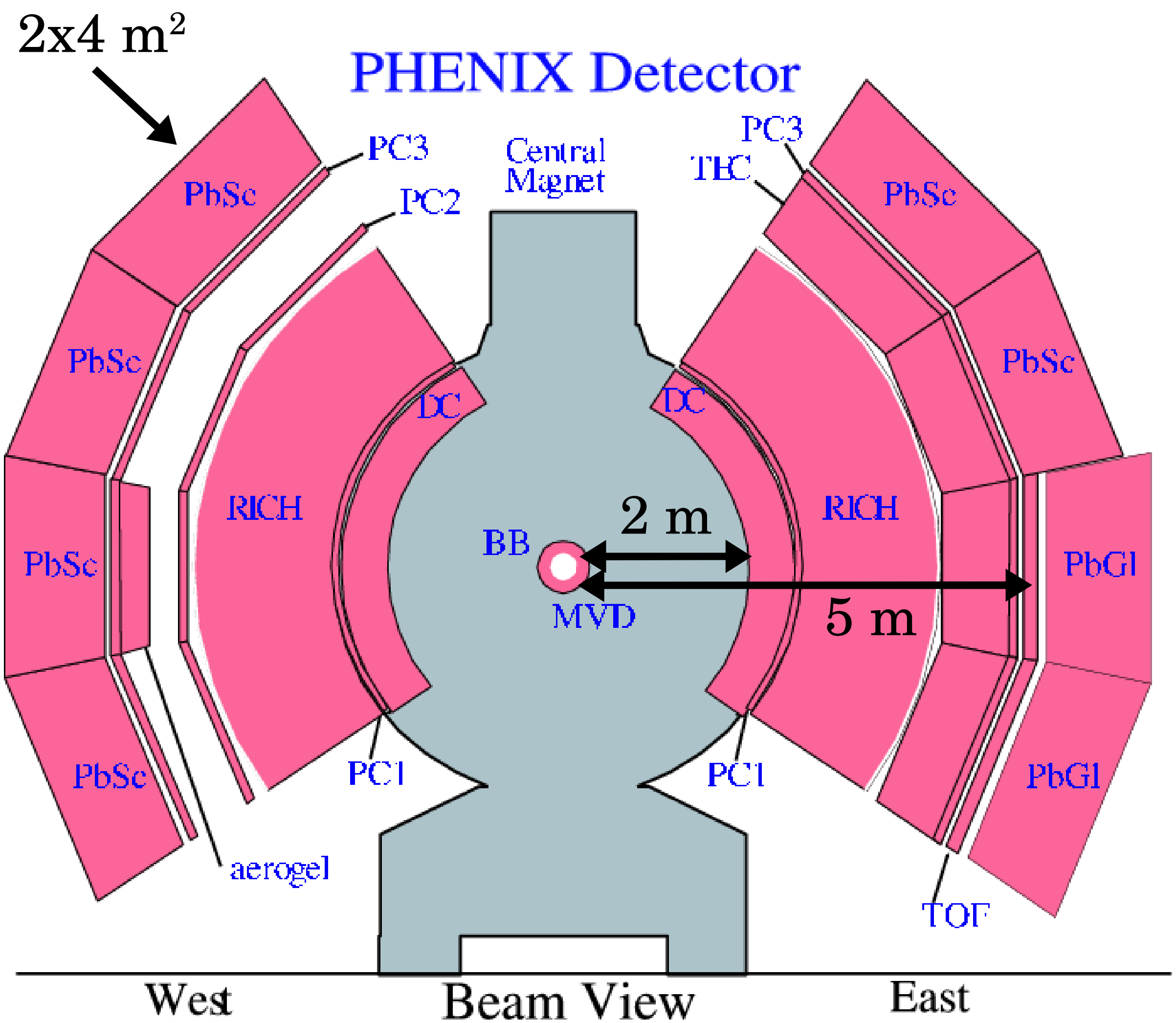
- Cross section in sideview



- Collision point, beam luminosity & minimum-bias trigger
  - With Beam-Beam Counter ... charged particles at 3.0<|η|<3.9
- Beam polarization direction at PHENIX IR
  - With Zero-Degree Calorimeter ... neutrons at ±2.8 mrad

PHENIX Detector – Central Arms

- Cross section in beamview
  - $\Delta\phi = 90^{o} \times 2$, $|\eta| < 0.35$



- Photons
  - With EMCal ...
    Lead Scintillator (PbSc) & Lead Glass (PbGl)
  - $\sigma_E/E \sim 8\%$ at 1 GeV
  - Fine segmentation, 0.01x0.01 rad/seg.
- Charged particles
  - With Drift Chamber (DC) & Pad Chamber (PC1)
  - $\sigma_p/p \sim 1.6\%$ at 1 GeV
- Trigger
  - High-energy photon (>~1.4 GeV) by EMCal

Measurement Methods

Jet Reconstruction

- Analyzed data
  - Integrated luminosity: 2.3 pb^{-1} taken in 2005
  - High-p_T (> 2 GeV/c) photon trigger ... largest statistics
  - Photons with $p_T > 0.4$ GeV/c (measured with EMCal)
  - Charged particles with $0.4 < p_T < 4.0$ GeV/c (measured with DC and PC1)

- Particles in one Central Arm were clustered
  - By a seed-cone algorithm with a cone radius $R = 0.3$

    ... this cone is as large as the Central Arm acceptance ($|\eta| < 0.35$)

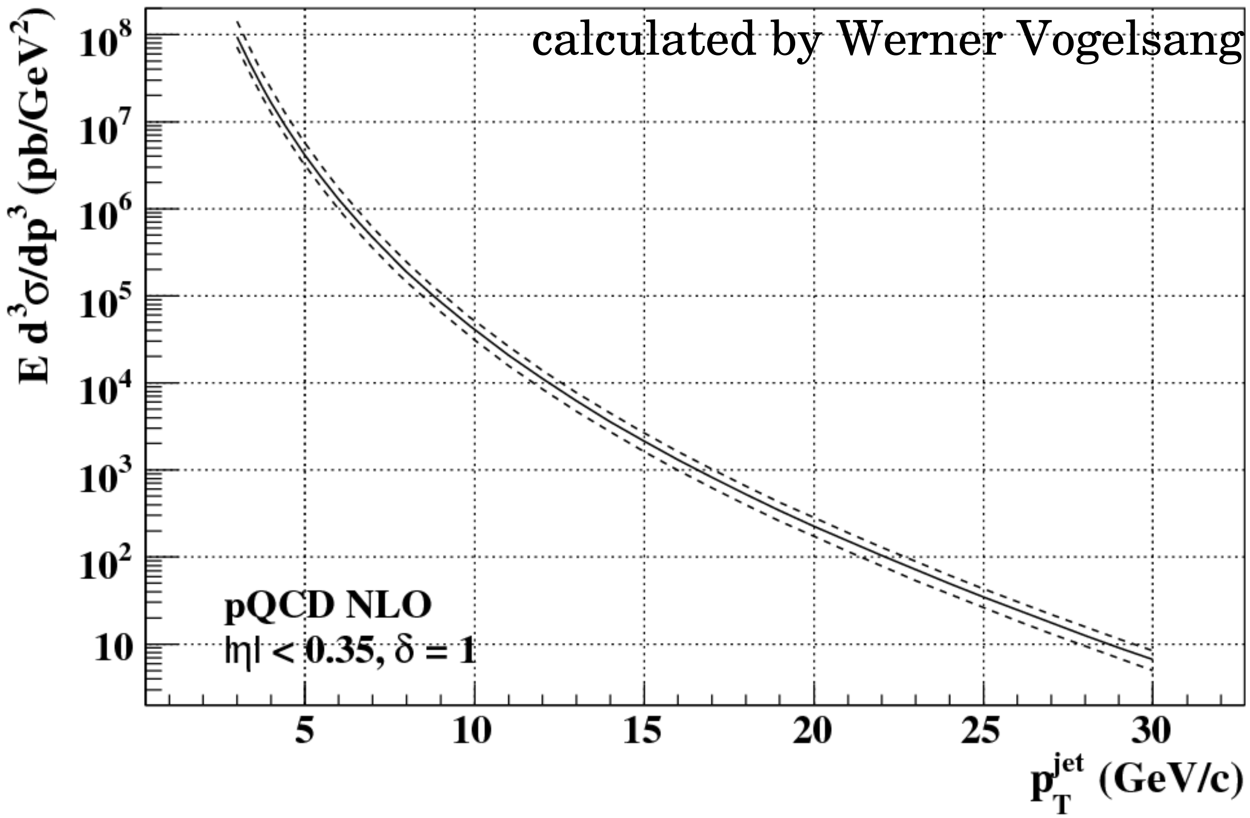
    $$R^i \equiv \sqrt{(\eta^i - \eta^C)^2 + (\phi^i - \phi^C)^2}$$
  - Choose the particle cluster having maximum p_T^{reco} in arm

    reconstructed-jet p_T: $\vec{p}^{\,\text{reco}} \equiv \sum_{i \in \text{cone}} \vec{p}_i$
    - n particle clusters from n seed particles, but largely overlapped
    - Splitting doesn't work well because of the limited acceptance

Prediction with NLO Calculation + Simulation

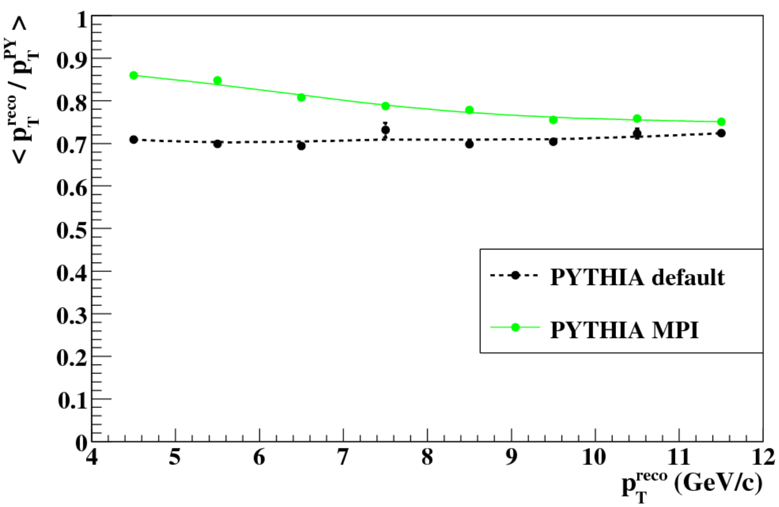
- NLO pQCD calculation
  - Parton-level jet with cone size $\delta = 1.0$
    - Larger δ to suppress jet splits, since the measurement is not sensitive to jet splits
    - Correction with full simulation

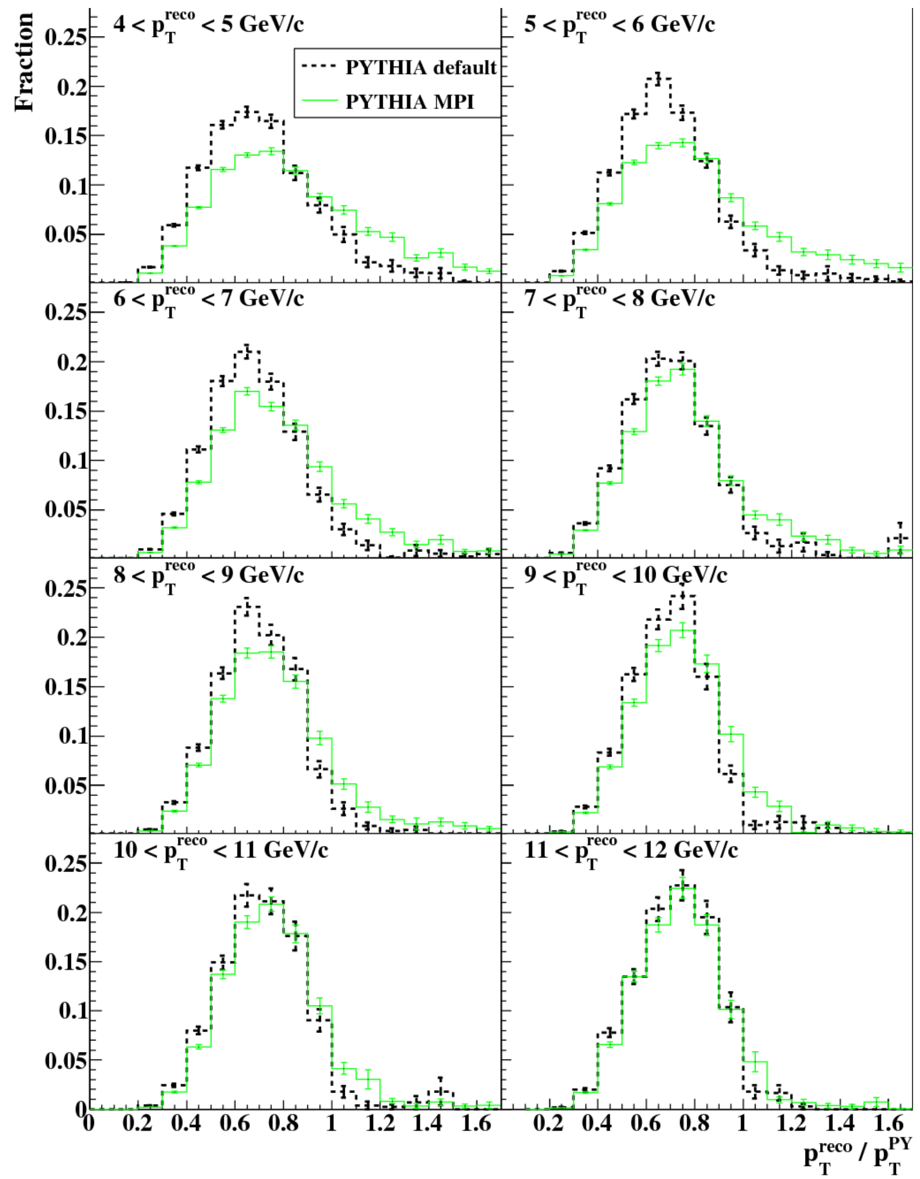
      parton-level jet with $\delta = 1.0$ –> hadron-level jet with $R = 0.3$
  - Cross section (& A_{LL} also) can be given



Prediction with NLO Calculation + Simulation

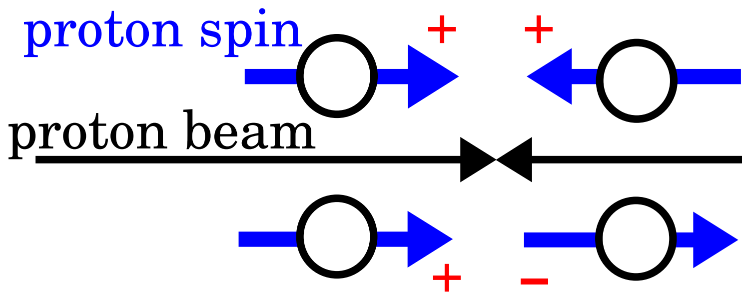
- PYTHIA+GEANT simulation
  - This is to evaluate the statistical translation from parton-level jets to hadron-level (reconstructed) jets
  - Parton-level jet in PYTHIA = one of hard-scattered partons
    - p_T in NLO calc. = p_T in PYTHIA
    - With 10% p_T scale error (which has been evaluated from the cone-size dependence of jet p_T in PYTHIA)





Measurement of ΔG with Jet Production

- Polarized proton-proton collisions
  - Two helicity (polarization) patterns: "+ + or – –" and "+ – or – +"



$\sigma_{++} = \sigma_{--}$

$\sigma_{+-} = \sigma_{-+}$

- Double helicity asymmetry

$$A_{LL} = \frac{1}{|P_B||P_Y|} \frac{(N_{++} + N_{--}) - R(N_{+-} + N_{-+})}{(N_{++} + N_{--}) + R(N_{+-} + N_{-+})}$$

N_{++}, N_{+-} : jet yield with "++" or "+–" helicity pattern

P_B, P_Y : beam polarization (~ 49%)

$R = L_{++} / L_{+-}$: relative luminosity (0.9 ~ 1.1)

  - Evaluate jet yields w/ each helicity pattern to obtain A_{LL}
  - Systematic errors cancel out in most cases
    (luminosity, trigger efficiency, detector acceptance, etc.)

Measurement of ΔG with Jet Production

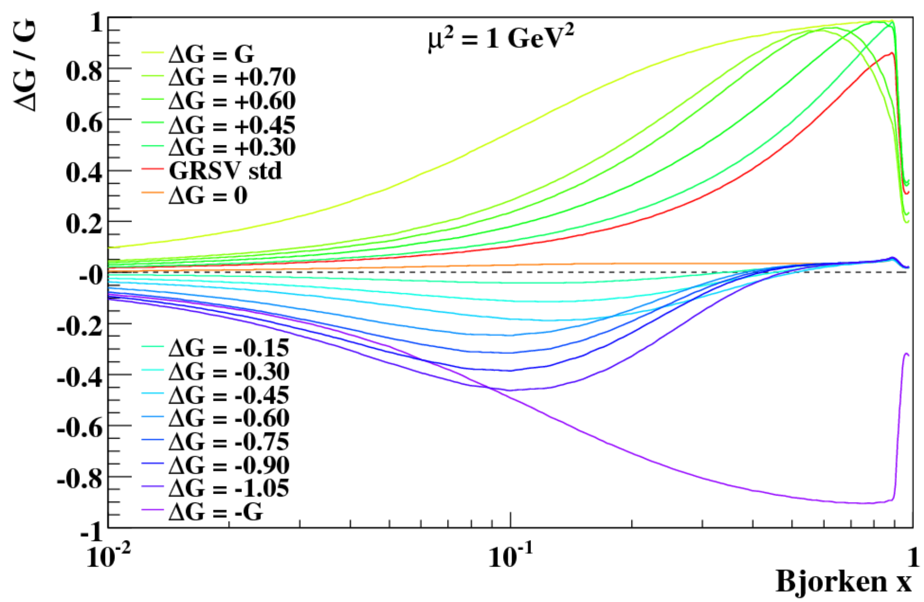
- Predictions of A_{LL} w/ NLO pQCD calculation + simulation

$$A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \xrightarrow{q+g} \frac{\int dx_1 dx_2 \ \Delta q(x_1) \cdot \Delta G(x_2) \cdot \Delta\hat{\sigma}^{q+g\to jet+X}}{\int dx_1 dx_2 \ q(x_1) \cdot G(x_2) \cdot \hat{\sigma}^{q+g\to jet+X}}$$

$\Delta\hat{\sigma} = (\hat{\sigma}_{++} - \hat{\sigma}_{+-})/2$: spin-dependent cross section of parton-parton scattering (calculable by pQCD)

- Apply simulation correction to derive reco.-jet A_{LL}
- Different x, Q^2, subprocess (q+g etc.) are convoluted in measured A_{LL}

  –> difficult to unfold measured A_{LL} to directly get ΔG
- Evaluate A_{LL} with various assumed ΔG & compare them with measured A_{LL} to find the most probable ΔG



Results

Measured Quantities

- Event structure ... multiplicity, p_T density & thrust
  - Check how PYTHIA MPI can reproduce the event structure in p+p collisions at $\sqrt{s}$ = 200 GeV
  - Confirm that simulation reproduces real data well

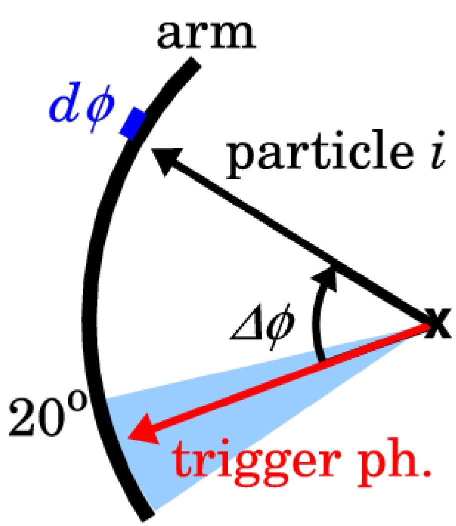
- Jet production rate
  - Confirm that the absolute yield of the measurement & the calculation are consistent (cf. A_{LL} is relative)

- Jet A_{LL}
  - Jet yields in two beam pol. pattern –> measured A_{LL}
  - pQCD theory and PYTHIA+GEANT simulation –> predicted A_{LL}
  - Compare the measured A_{LL} with the predicted A_{LL} to find the most probable ΔG

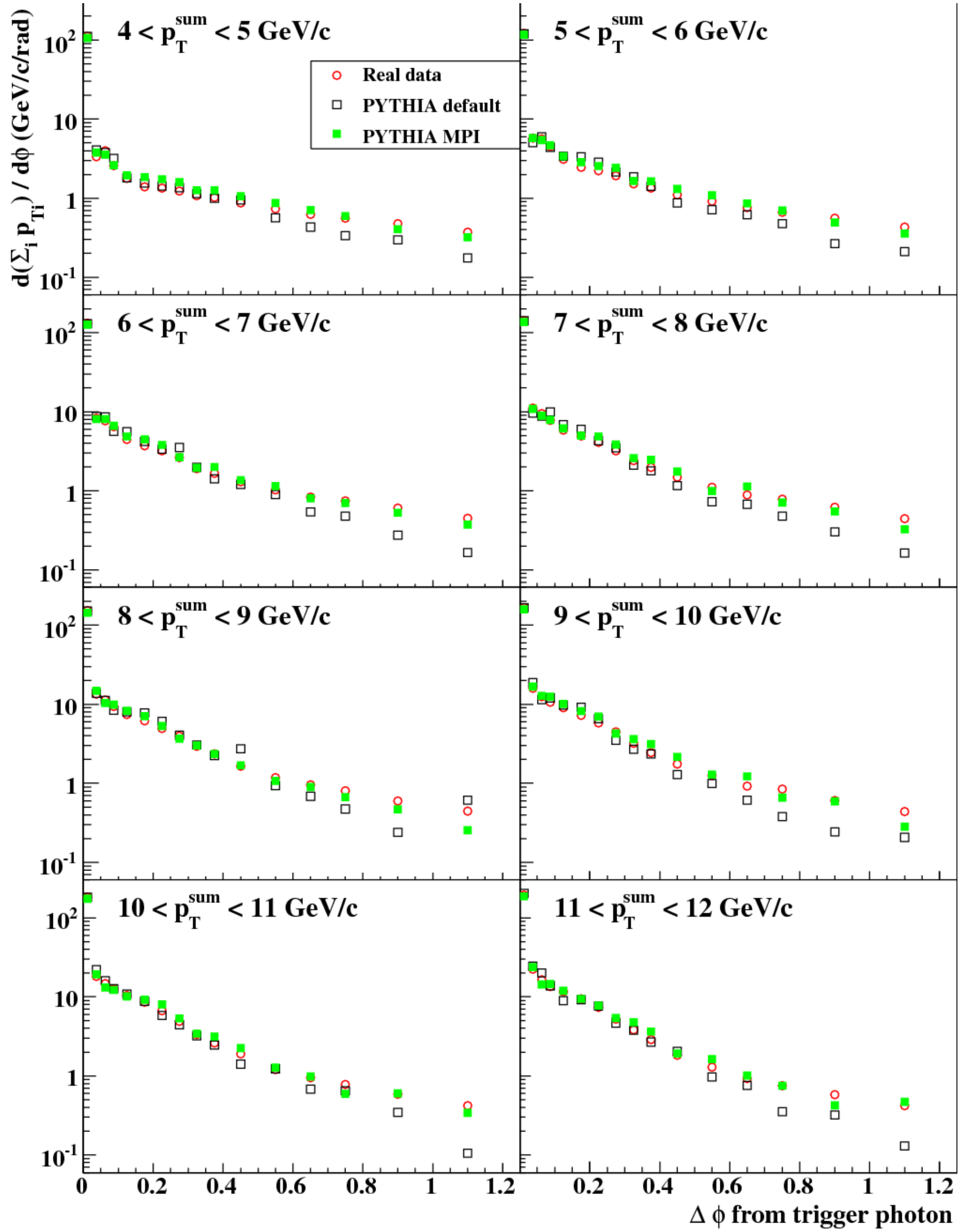
Event Strucure – p_T Density

- Sum of p_T of particles at $\Delta\phi$ from trigger photon

$$\mathcal{D}_{p_T}(\Delta\phi) \equiv \left\langle \frac{1}{\delta\phi} \sum_{i \text{in} [\Delta\phi,\ \Delta\phi+\delta\phi]} p_{Ti} \right\rangle_{\text{event}}$$



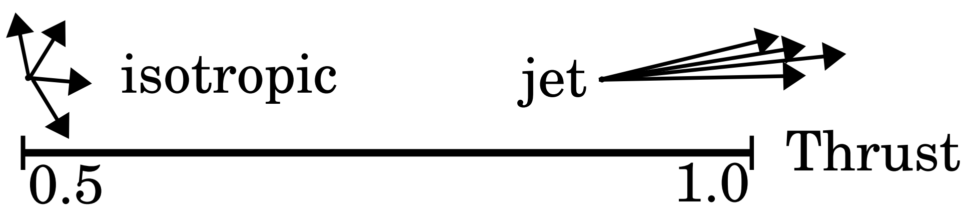
- Jet shape (at small $\Delta\phi$)
  - PYTHIA MPI (& def.) OK
- Underlying event (at large $\Delta\phi$)
  - PYTHIA MPI OK



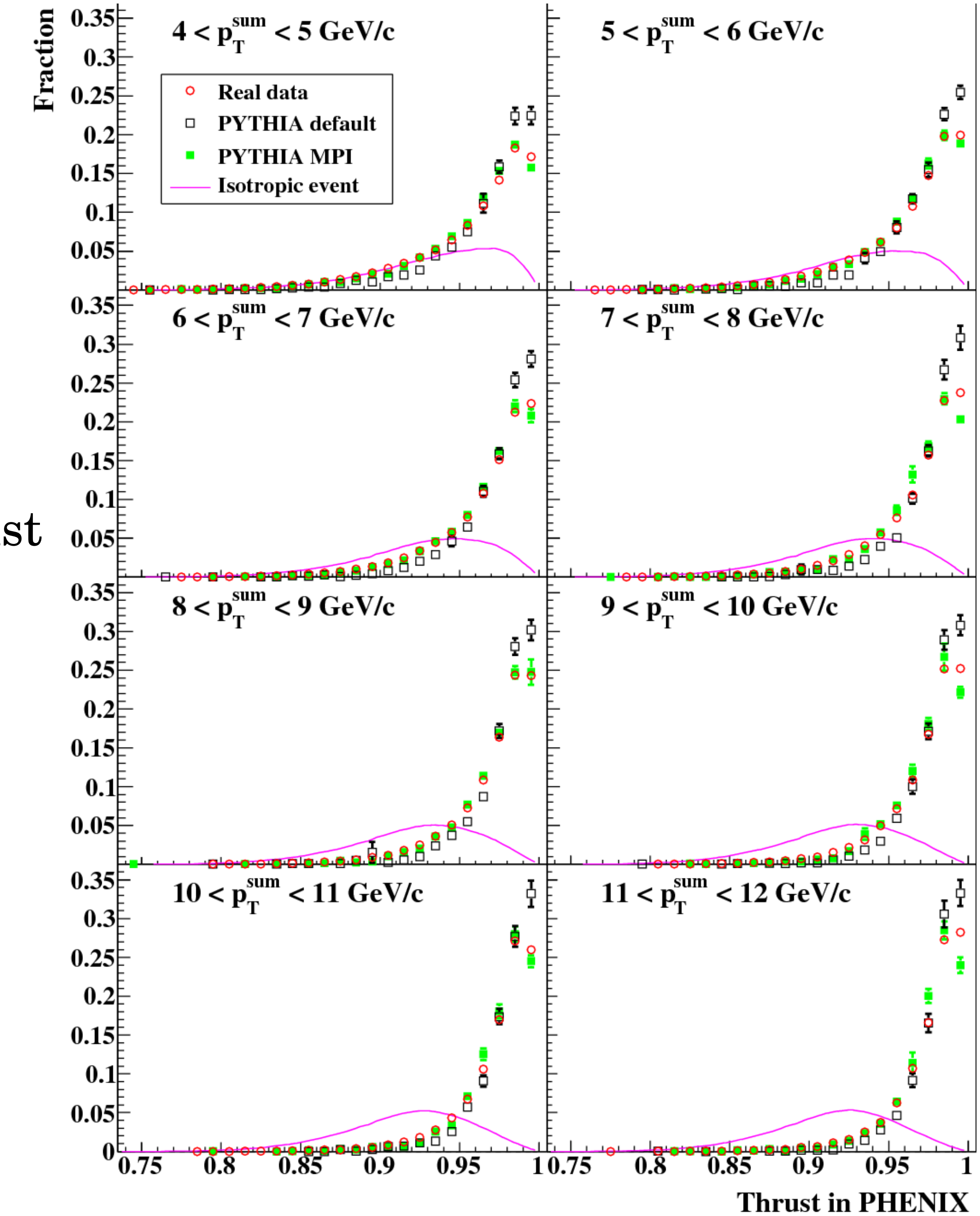
Event Structure – Thrust

- How much particles are concentrated in one direction

$$T_{PH} = \frac{\sum_i |\vec{p}_i \cdot \hat{\vec{p}}|}{\sum_i |\vec{p}_i|}$$



- PYTHIA MPI agrees with real data



Jet Production Rate

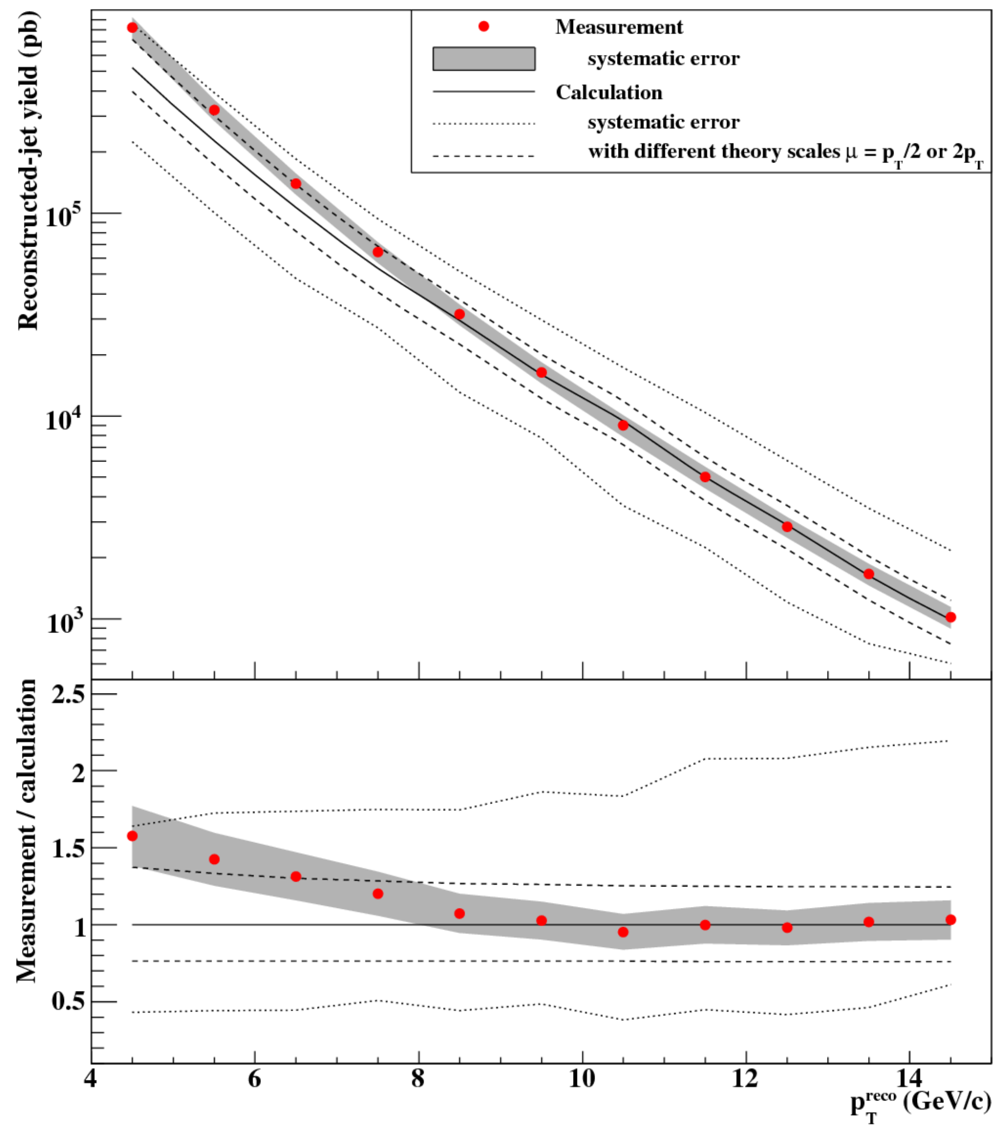
- Reconstructed-jet yields corrected for trigger efficiency

$$\mathcal{Y}^i \equiv \frac{N^i_{reco}}{L \cdot f_{\mathrm{MB}} \cdot f_{ph}}$$

  - Main systematic errors

Source	Size	Size on rate
Measurement		
Luminosity	9.7%	9.7%
EMCal energy scale	1.5%	7-6%
Tracking momentum scale	1.5%	0-3%
Calculation		
Jet definition	10% in p_T	30-70%
Jet shape & underlying event	–	50-20%
High-p_T photon fragmentation	–	10%
Simulation statistics	–	2-5%

  - PYTHIA MPI agrees with real data within errors

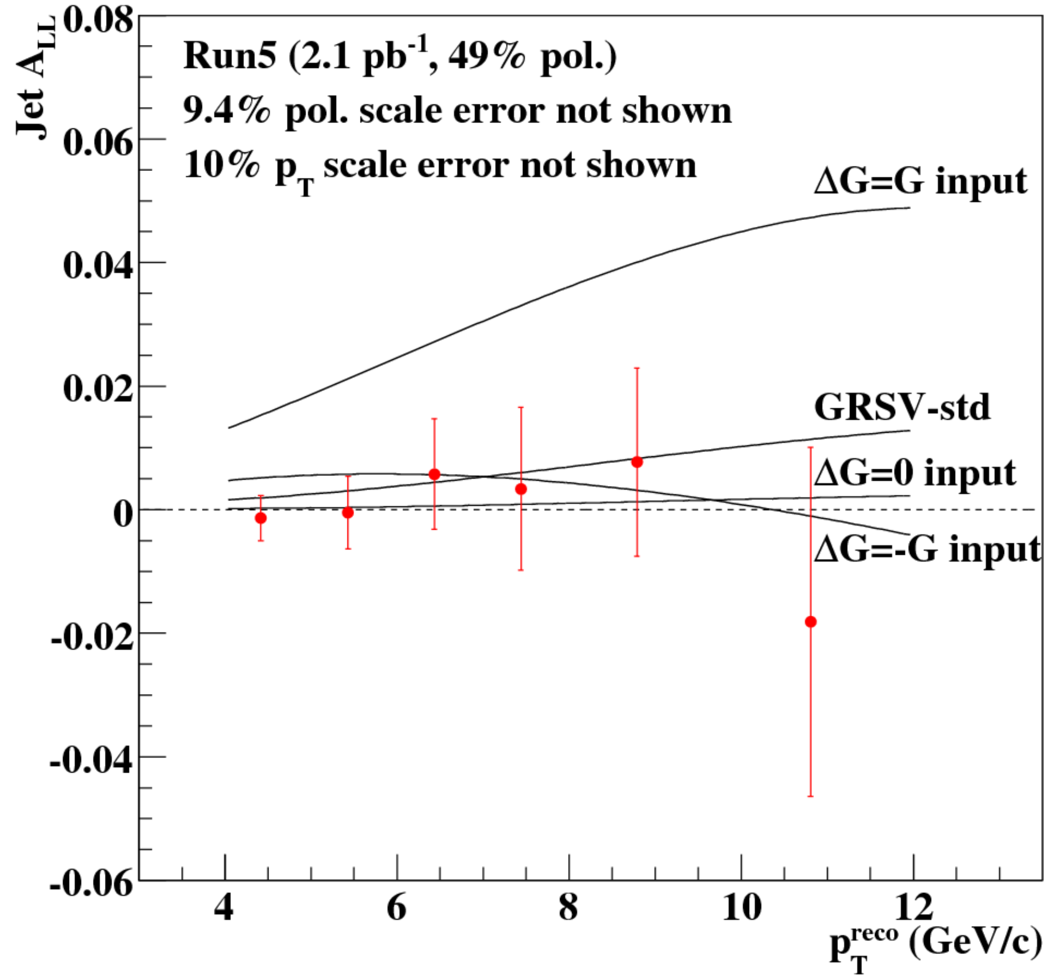


Double Helicity Asymmetry

- Reconstructed-jet A_{LL}

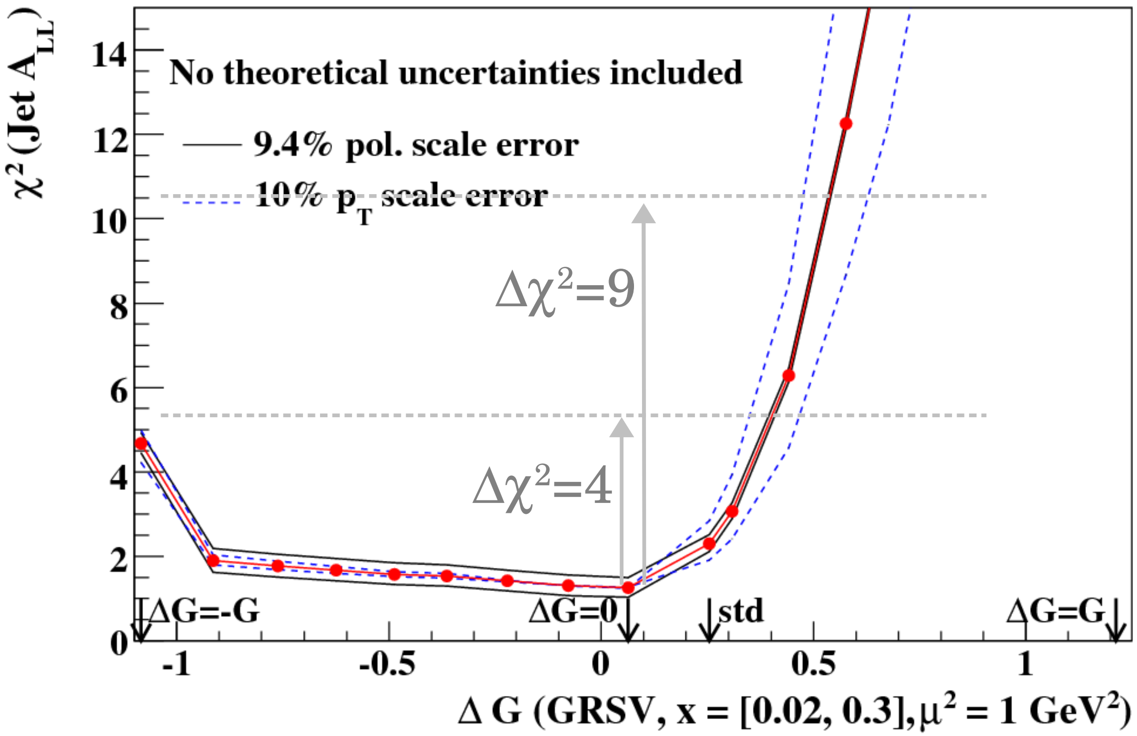
$$A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

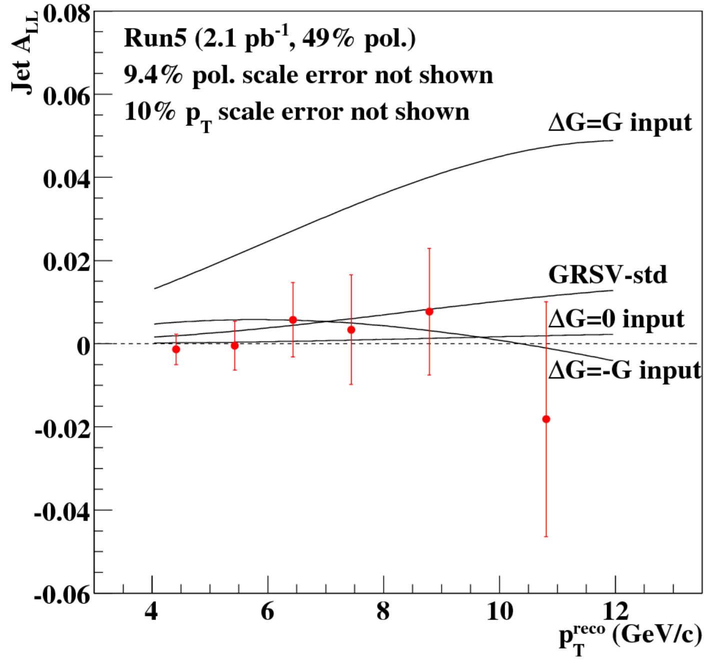
  - Stat. error dominates
  - Systematic errors
    - Jet definition ... 10% in p_T
    - Beam pol. error ... 9.4%
    - Other errors (luminosity, measured energy & mom. scales, etc.) are negligible in A_{LL}



Constraint on ΔG

- Comparison of measured & predicted A_{LL}





- $0.02 < x_{gluon} < 0.3$ ... probed by reco. jets with $4 < p_T^{reco} < 12$ GeV/c
- In GRSV parametrization, at $0.02 < x_{gluon} < 0.3$ and $Q^2 = 1$ GeV^2

$$-1.1 < \int_{0.02}^{0.3} \Delta G^{GRSV}(x, \mu^2 = 1) < 0.4 \qquad \text{as 95\% confidence interval}$$

$$\int_{0.02}^{0.3} \Delta G^{GRSV}(x, \mu^2 = 1) < 0.5 \qquad \text{as 99\% confidence interval}$$

Conclusion

- The event structure & the double helicity asymmetry (A_{LL}) of jet production at mid-rapidity ($|\eta| < 0.35$) in longitudinally polarized p+p collisions at $\sqrt{s} = 200$ GeV was measured
  - This is the first measurement of inclusive jet production at PHENIX to determine ΔG (arXiv:1009.4921)
- The MPI-enhanced PYTHIA simulation agrees well with the real data in terms of the event structure (multiplicity, p_T density, thrust)
- In A_{LL} measurement
  - Photons and charged particles were clustered by the seed-cone algorithm with a cone radius $R = 0.3$
  - The PYTHIA+GEANT simulation was used in relating the NLO calculation to the real data
  - A_{LL} was measured at $4 < p_T^{reco} < 12$ GeV/c –> $0.02 < x < 0.3$
  - The comparison with the calculated A_{LL} imposed the limit

$$-1.1 < \int_{0.02}^{0.3} \Delta G^{GRSV}(x, \mu^2 = 1) < 0.4 \quad \text{as 95\% confidence interval}$$

$$\int_{0.02}^{0.3} \Delta G^{GRSV}(x, \mu^2 = 1) < 0.5 \quad \text{as 99\% confidence interval}$$